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BRUCE NGS - HIGH FREQUENCY SOIL PARAMETER TESTS

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Tests of Bruce NGS soil parameters were completed as one task of a larger project to develop tools for simulating transient potentials on station grounding systems. These potentials, resulting from lightning strikes, switching transients or power system faults and coupled through station control wiring, may upset operations or damage sensitive equipment. This task covered a literature review and tests for estimating the conductivity σ, permeability μ and permittivity ϵ over frequencies extending from 60 Hz to 10 MHz for the fill material found at Bruce GSA and GSB.

1.0 INTRODUCTION

The Electrical Research Department is investigating the high frequency performance of grounding systems and station wiring at the request of the Electrical Controls Engineering Department. The objective is to develop quantitative tools for analyzing the effect of stresses such as lightning strikes, switching transients or power system faults relative to the dielectric capability and interference immunity of equipment. These tools will allow designers to calculate the benefits of various grounding system options in a cost-effective manner. Similar methods are presently available to optimize the 60 Hz performance of grounding conductors [1]. Further details regarding the project background and task subdivision are provided in Appendix A.

The propagation of high frequency transients on conductors, whether buried, embedded in concrete or otherwise located in a powerhouse, can be simulated if the per unit length resistance R, inductance L, conductance G and capacitance C are known. For the meshed geometries common on grounding systems, these per unit length parameters may need to be full matrices since the mutual coupling between neighbouring conductor segments is important. Direct solution of the voltage and current waveforms from these distributed parameters may be possible for some simple geometries. More generally, it will be necessary to subdivide the conductors into a sufficient number of lumped segments and use network solution methods over a number of fixed frequencies, followed by conversion to the waveforms over time.

In principle, the above per unit length parameters can be calculated from the conductor geometry, the soil conductivity σ, permeability μ and permittivity ϵ. For example, the calculation of mutual L and R between two non-parallel conductors of finite length is similar to, but more complex than, finding a Carson impedance where one conductor is assumed to be infinitely long. Since the matrix of coupled conductors may contain many such elements, efficient techniques will be needed to make calculations practical on small computers. This task establishes estimates for σ, μ and ϵ from 60 Hz to 1 MHz.

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2.0 LITERATURE SEARCH

The conductivity σ of soil in Siemens per metre is the inverse of resistivity, a parameter commonly measured in grounding system studies because it varies so widely for different soil types. Conductivity is used in this study because at high frequencies it is closely related to permittivity ϵ, both of which vary due to similar mechanisms. The permeability μ describes the ability of soil to store magnetic energy. It is usually assumed to remain constant at μ_0, equal to 0.4 π μH/m, unless ferromagnetic minerals such as magnetite increase the stored energy density [2].

The permittivity describes the ability of soil to store electric (field) energy. For vacuum, ϵ_0 has a value close to 8.85 pF/m. On a base of ϵ_0, air has a relative permittivity ϵ_r close to 1.0. For most dry solid dielectrics, ϵ_r ranges from 2 to 5, related to energy stored in distorting the pattern of atomic electrons in the presence of an external electric field. For certain pure liquids such as water, ϵ_r can reach much larger values of about 80. In these materials the molecules have unevenly distributed charge, and in the presence of an external field, can flip to become aligned (polarize). The mutual repulsion of adjacent molecules now stores additional energy. The effective permittivity may be further increased in compounds or mixed materials, for example by electrochemical effects or through conductive grains separated by thin insulating films.

Polarization takes time to occur and the permittivity will eventually decrease as the frequency is raised. Near the corner frequency, dielectric losses and thus conductivity also increase dramatically. This behaviour has been represented in an equivalent circuit (Debye model) as a high frequency capacitance in shunt with a series resistor and capacitor representing lower frequencies [3]. For water the corner frequency occurs at about 1 GHz, a frequency exploited in the ubiquitous microwave oven. For complex materials such as soil, a number of Debye time constants are active at much lower frequencies [2]. The frequency dependency varies widely for different materials and has to be empirically measured.

Figure 1 shows typical conductivities for soil and rock on log-log scales (base ten) measured from 60 Hz to 3 GHz and derived from a literature review. Note the large dynamic range, a factor of ten million, represented on the ordinate. Traces S3 to S15 measured by S. Visacro in clay (presumably Brazilian) show a strong correlation between conductivity and water content, defined in the suffix to S as a percentage of dry sample weight [4]. Conductivity is almost constant from 1 kHz to 1 MHz and varies approximately with the square root of frequency below 1 kHz. Traces H0 to H20 were obtained by Hipp for gray San Antonio clay loam at higher frequencies using a coaxial sample chamber [5]. Here conductivity is also correlated with water content. Conductivity begins to increase again with frequency near 1 GHz, in line with the Debye model for pure water.

Trace F, measured by Fuller and Wait for rock in situ near Raymond, Colorado, contains less water giving lower and fairly constant conductivity from 100 Hz to 10 MHz [2]. Traces A0.04 to A2.4 were obtained by Amano for granite, sandstone, mineralized ore and organic soil respectively [6]. As with H0, these rather dry samples show conductivity increasing linearly with frequency, which may be caused by a constant permittivity and dielectric loss tangent δ equal to $\omega \epsilon / \sigma$. Finally, trace VH applies to de-ionized water, showing very low conductivity below the Debye loss mechanism occurring near 1 GHz [3]. Trace F may be the most representative for moist granular fill material below 1 MHz, assuming modest proportions of clay which has higher conductivity and greater frequency dependency. Under this inference, the conductivity of Bruce soil should be fairly constant with a tendency to rise beyond 1 MHz.

Figure 2 shows a similar plotting of measured permittivity on log-log scales with the ordinate covering a range of one thousand. The soils associated with traces F, A0.04 to A2.4, VH and H0 to H20 were described above, while trace V was provided by Vance for sandy or loamy dry soil. The graph shows that dry soil or rock has a fairly constant ϵ_r over frequency between 3 and 7 while pure

water is constant at about 78. At low frequencies, wet soil can have a frequency dependent ϵ_r exceeding 1000, in line with the multiple Debye model. Based on this information, the relative permittivity of Bruce fill material may vary from about 1000 at 100 Hz, to 100 at 10 kHz, to 10 at 1 MHz.

3.0 EXPERIMENTAL TECHNIQUES

3.1 Wenner and Related Arrays

Figure 3 shows the Wenner array commonly used to measure soil resistivity or conductivity for grounding studies. Four in-line probes at equal spacing s are used with current applied to C1 and C2 and potential measured across P1 and P2. For a measured ratio of current to voltage or admittance Ym, the soil parameters

$$\sigma + j\omega\epsilon = Ym / (2\pi s) \qquad (1)$$

Here Ym must be measured as a complex quantity using a two channel network analyzer with magnitude and phase output. This was implemented with a Hewlett Packard 3570A analyzer driven by a 3330B sine wave generator. A microcomputer was used for control, data storage and spreadsheet analysis. As shown in the figure, a high frequency balanced/unbalanced (balun) transformer ensured that the grounded-source generator applied equal and opposite currents to C1 and C2. A Pearson model 410A wide-bandwidth transducer supplied a current signal to analyzer channel "A", while a second balun fed the differential voltage between P1 and P2 to single-ended channel "B".

Since inductive coupling between parallel test leads might introduce a fictitious negative permittivity, other array geometries were investigated. Figure 4 shows the final selection, which also has a response given by (1), assuming s to be much smaller than the distances to the remote probes. The inductive coupling between current and potential leads is now theoretically zero, since they are perpendicular. The high impedance (FET) input probe reduced the loading on probe P1 by the coaxial cable. With P2 practically at zero (remote) potential, no balun was necessary on analyzer input "B".

3.2 Sample Chambers

Figure 5 shows a simple chamber constructed for measuring soil samples brought into the laboratory. Test current was applied between the upper screen and aluminum cake pan in one corner while the potential was measured at the opposite corner and fed to the above network analyzer. A balun in the potential input cable provided isolation to keep test current from circulating in this circuit. Polyethylene film above the screen kept the sample from drying out while the foam and plywood applied reproducible pressure. The stray capacitance on the edges and upper surface of the screen was calibrated out by measuring the change in admittance for two known air gaps in the sample area.

The stray capacitance might be eliminated, and the accuracy increased in future tests, by sandwiching the test screen between two guard screens at the same voltage but connected to the source ahead of the current transducer. With this change the transducer would measure only that component of current passing through a hole of known area cut into the lower guard. The chamber calibration factor could then be calculated using the simple parallel plate formula since all current streamlines in the sample near this hole would be vertical.

As frequencies increase, the inductive coupling between test leads becomes increasingly difficult to control and an alternative is to place the sample in a distributed line [3,5,6]. The parameters are then calculated from the line length and standing wave ratios present at particular frequencies. Since preliminary tests showed the sample chamber to give consistent results to 10 MHz, these alternatives

were not investigated. Drawbacks for all chamber methods include the uncertainty associated with disturbing the soil and the effort required to obtain samples below the surface.

3.3 High Frequency In Situ Measurements

Due to limitations experienced with the in situ Wenner and related arrays of Section 2.1, several alternatives based on the measurement of a self or driving point admittance were investigated.

3.3.1 Buried Rod Dipole

Figure 6 shows a simple distributed system based on criss-crossed ground rods or probes normally used for Wenner testing. Two such rods symmetrically driven are fairly easy to install but require an impedance detector with balanced terminals. The alternative is an unbalanced array using a single vertical rod and a radial crowfoot reference mesh near the surface, but this was judged awkward to configure. Note that the rods must be closely spaced to minimize inductive coupling between current and potential lead connections. The differential admittance Yd measured at the terminals allows calculation of the soil parameters

$$\sigma + j\,\omega\,\epsilon \;=\; Yd\,(\ln(s/a) + \ln(s/2h) - 2 + 3h/s)\,/\,\pi s \qquad (2)$$

where a is the rod radius, of length s in soil, at average depth h. This expression was derived from the rod self and mutual resistances, obtained by comparing the resistance to remote ground of an individual rod and the two in combination [8]. Note that the parameters are averaged over the "zone of influence" of the dipole, so the depth surveyed is limited to length s. The expression also assumes that the rod lengths are short compared to a wavelength in soil, which should be valid below 10 MHz for s under a metre.

Figure 7 shows how a balanced impedance detector was constructed. The network analyzer was installed in a truck equipped with a portable power supply. Three 50 Ω-terminated cables 15 m long helped to eliminate proximity between the truck and dipole. Four-wire type current and potential connections were made to the dipole as shown by the ± terminals. Current and potential circuits were separated and individually twisted to reduce stray inductive coupling. In order to reduce crosstalk in the 15 m cables, signal levels were coordinated to about - 30 dBm by providing a 40 dB RF amplifier as shown. A 5 W, 50 Ω output load was found helpful in preventing parasitic oscillations in the amplifier. The amplifier power lead and three signal cables were closely spaced on the ground in a direction perpendicular to the dipole. Baluns provided isolation to balance the signal applied to the dipole. The sending balun was home-brew, and to the author's knowledge of unique design, as shown in Figure 8. Breaking the primary winding braid at the 50 % point ensures that the secondary winding is balanced about zero potential, taking capacitive coupling between primary and secondary windings into account.

Voltage was sensed by a divider to increase the loading impedance of the 50 Ω potential cable to 2500 Ω. Even this loading was eliminated using a 2500 Ω compensating resistance and winding on the Pearson current transducer as shown. Shunting the 2500 Ω resistor with small capacitors (several picofarads) also allowed stray capacitances on the test leads to be compensated.

3.3.2 Surface Bowtie Dipole

Figure 9 shows an array with characteristics similar to the above, but located on the surface. This may be easier to install on granular fill material, although ensuring good contact between the screen

and the soil may be difficult. The soil parameters may be calculated from the measured differential admittance Yd as

$$\sigma + j\,\omega\,\epsilon \;=\; 2\,Yd\,\ln(2\pi s/w)\;/\;\pi s \qquad (3)$$

where s is the length of each half bowtie and w is its maximum width. This expression was derived from the propagation parameter and impedance of a cone, flattened to a wedge but with the perimeter maintained [7]. Displacement currents in air were neglected. Good contact to the soil may become less critical as the bowtie area is increased, although s should be kept less than 2 m at 10 MHz to avoid having to include wavelength effects in the analysis.

3.3.3 Surface Braid Diamond

Figure 10 shows a diamond-shaped array constructed out of uninsulated braid conductor. When laid on gravelled surfaces, direct contact (electronic conduction) to the ground is probably negligible and trenching may have to be used to improve the connection. The admittance is measured in the lower corner while the upper corner are either shorted or left open. Due to the symmetry of the diamond, these terminations should be fairly representative of a single phase transmission line, with the far end shorted or open, which allows simplified standing-wave analysis. Again the size of the diamond was varied by coiling surplus braid at the far end.

3.3.4 Surface Cable Dipole

Figure 11 shows a fourth variation on dipoles, this time based on an insulated cable. The insulation may help to improve the reproducibility of contact between the conductor and soil, which for bare conductors of relatively small diameter can be expected to be ill-determined. Cables up to 25 m in length were now tried, which would probe deeper into the ground, but would require taking standing waves into account. Since the far end is always open circuited, some assumptions have to be made in the analysis of results in order to resolve the soil parameters. Intermediate lengths were obtained by coiling the cable ends as shown.

4.0 MEASURED RESULTS

4.1 Wenner and Related Arrays

Measurements using the Wenner array of Figure 3 were conducted on the front lawn of the Research labs during September 1990. The conductivity was observed to increase linearly with frequency above ten kilohertz while permittivity was negative at all frequencies. An explanation is provided by the Carson coupling impedance between the parallel current and potential leads. For the resistive portion of the Carson impedance to stay small compared to the measured resistance, maximum s was found to vary inversely with the square root of frequency. For an error under ten per cent in 20 Ωm soil, s must be less than 70 and 7 m at 60 and 6000 Hz, respectively. For the reactive portion of the Carson impedance to be small compared to the measured reactance, s must be less than 0.02 m, assuming 1000 Ωm soil, a 1 m spread between leads and an ϵ_r of 10. The allowable s varies inversely with the square root of the mutual coupling and is independent of frequency. Thus the Wenner array may be useful only for measuring conductivity below a few kilohertz and is unsuitable for estimating permittivity.

The modified Wenner array in Figure 4 fared better in the sense that positive permittivity was measured for s under 1 m. From the above relations, it appears that the perpendicular routing of leads reduced Carson coupling by a factor of several thousand. Further improvements in performance were attempted by using two slightly diverging potential leads connected to separate probes at P2, and a zeroing potentiometer to nul out the Carson reactive coupling. The optimum setting was found to

vary with frequency and measurements using this method were halted. The array does have an advantage in using independent current and potential electrodes, eliminating errors due to uncertain soil contact. The method is recommended for further development.

4.2 Sample Chambers

A two-day visit was made to Bruce NPD on October 16 and 17, 1990. The first day covered meetings with site staff to discuss the nature of problems experienced, and to plan for tests the second day. These were conducted immediately west of the Bruce GSA powerhouse on imported fill material, and at the railway siding area west of the main security gate for the complex. Figure 12 shows sample chamber results for soil bagged in plastic at the second site. The weather had been wet over the previous week but with no rain on the test day. Comparing the measured relative permittivity of 18 at 10 kHz with values in Figure 2 shows that this sample probably contained less than 1 % water. This is consistent with the slightly moist, granular and sandy texture observed for the sample. The dashed line, varying inversely with the square root of frequency, represents the behaviour expected from the literature survey. There is general agreement between measured and expected results below 100 kHz. Similar frequency dependency in permittivity was observed for samples of fill material taken west of Bruce GSA, although the maximum value reached 52 at 10 kHz. The conductivity remains fairly constant at 0.2 mS/m (5000 Ωm) below 100 kHz and then approximately doubles by 1 MHz. This low value is another indicator of the low water content.

Figure 13 repeats measurements on the above sample with about 10 % water added, by weight. The relative permittivity increased by a factor of almost ten with greater frequency dependency while conductivity increased by 25 to 5 mS/m (200 Ωm) below 100 kHz with less of an increase at higher frequencies.

4.3 High Frequency In Situ Measurements

4.3.1 Buried Rod Dipole

A buried rod dipole with the dimensions shown in Figure 6 was used to make in situ soil measurements at the railway siding area. Due to the granular nature of the soil and vibration from driving the rods, a narrow coaxial zone of disturbed soil around the rods was expected to affect the results. This has been handled by subtracting from the measured impedance a compensation impedance, derived from a shunt conductance of 1.6 mS and a lumped capacitance of 400 pF. These values were chosen so the permittivity matched, as closely as possible, an inverse square root relationship with frequency. The 400 pF capacitance can be physically related to an average air gap of 0.1 mm around each rod due to vibration.

Figure 14 shows the soil parameters obtained from (2) and the above compensated admittance. The measured permittivity follows rather closely the expected frequency dependency, again shown by the dashed line, below 2 MHz. Similar results were noted for the test site near Bruce GSA. The peak value of 160 at 100 kHz is quite large compared to 8 to 30 measured in the sample chamber. This may give an indication that permittivity is sensitive to disturbed soil, with reduced packing density.

4.3.2 Surface Bowtie Dipole

The array shown in Figure 9 was deployed at both Bruce sites with results for the railway yard area shown in Figure 15. Again compensated reduction of the measured impedance was used, in this case 0.2 mS in shunt with 800 pF. These may be physically related to a contact resistance of 5000 Ω and average air gap of 2.5 mm on the rough granular surface. The permittivity at 100 kHz is about half that seen in Figure 14. However, up to 2 MHz its frequency dependency is a very good fit to the

expected value. Note the conductivity is much lower than that seen in Figure 14, which may be a consequence of lower water content in the surface layer.

4.3.3 Surface Braid Diamond

A spreadsheet was used to derive the propagation parameter $\alpha + j\beta$ and the complex surge impedance from the driving point impedances measured with the far end of this transmission line open and shorted. From these quantities, the per unit length line parameters R, L, G and C mentioned in the introduction were found as shown in Figure 16. As a final step, μ, σ and ϵ should be calculated from the geometry of the braid in relation to the soil surface. However, this was not attempted because G and C in the figure were estimated to be almost completely determined by the capacitance between the braid and the soil surface as well as stray leakage where the braid happened to touch the moist soil. Better conditioned results would probably require the braid to be trenched into the ground.

4.3.4 Surface Cable Dipole

Similar analysis was used as above except that only open circuit line results were available. Since the complex surge impedance there had been fairly smooth over frequency, its magnitude and phase angle were here assumed to have a constant, and a linear frequency component. The complex propagation coefficient was then calculated from the test results and plotted while varying the assumed impedances parameters. Figure 17, obtained from the 25 m dipole at the railway siding area, shows that the propagation coefficients are fairly linear over frequency as expected. The results of this model then allowed calculation of R, L, G and C as shown in Figure 18.

The quality of these parameters appears better than in Figure 16, with R and G increasing while L and C are decreasing over frequency. The cable insulation, its longer length and larger diameter probably contributed to this improvement. Further studies are needed to see if the calculated soil parameters are consistent with those measured earlier.

5.0 DISCUSSION OF RESULTS

5.1 Based on a survey of the literature, the conductivity of fill material surrounding grounding grid conductors at Bruce NGS may be fairly constant below 1 MHz. Permittivity may vary inversely with the square root of frequency.

5.2 The classic Wenner array is unsuitable for high frequency soil testing due to excessive mutual coupling between current and potential leads. Routing these leads at large separations is theoretically beneficial, but wavelength effects in long conductors will upset the results. Shielding of these leads is impractical because shield currents would disturb the test configuration. The Wenner array can be useful for measuring soil conductivity at power frequency, with values at higher frequencies assumed to remain constant.

5.3 The perpendicular Wenner array has the potential to deliver in situ test data which is insensitive to contact anomalies, for example due to soil disturbances caused by driving in a rod. However to make it a practical test tool, effective methods must be found to reduce further the stray inductive coupling between test leads. This might take the form of differential A - B type measurements, where the measured admittance is supplemented by a known admittance derived from resistors and capacitors. This method was also found to be fairly sensitive to external electromagnetic noise pickup in the 100 kHz range.

5.4 The sample chamber results generally support the frequency dependent characteristics predicted by the literature survey. In comparison to the in situ measurements, the permittivity is about half as large. Errors are probably introduced through disturbing the soil,

the lower packing densities compared to in situ conditions and the difficulty of establishing good contact between an electrode and the sample surface.

5.5 The buried rod dipole results closely support the expected frequency dependency if compensation is made for the lower conductivity and permittivity of small air gaps near the driven rod surfaces. A disadvantage of this method is that the results may be sensitive to anomalies in the soil close to rods.

5.6 The surface bowtie dipole gave results similar to the buried rod dipole except for slightly lower permittivity and much lower conductivity. These differences may be related to the lower water content present near the soil surface. The bowtie covers a larger area than the rods, and thus has the virtue of giving results averaged over a larger volume of soil.

5.7 The surface braid diamond gave results of lower quality than the other methods because the per unit length capacitance was unduly sensitive to the small conductor diameter and its uncertain contact to the granular surface. Improvements could be based on trenching the braid or using rather wider screening on the surface to increase capacitive coupling to the soil.

5.8 The surface cable dipole was probably the easiest to install and can be conveniently extended to fairly long lengths. Large dimensions are a virtue in order to resolve soil parameters at greater depths. The use of insulation appeared to remove uncertain contact associated with the bare conductors laid on the surface. A limitation is the need to assume surge impedance parameters in order to resolve the per unit length parameters. Using a wider screen, insulated from the ground by a polyethylene film, may offer further improvements in performance.

6.0 CONCLUSIONS

6.1 Soil conductivity σ is fairly constant below 1 MHz and is estimated efficiently from low frequency Wenner testing. The relative permittivity ϵ_r varies approximately with the inverse square root of frequency. Typical values for Bruce GSA fill material are 1000, 100 and 10 at 0.1, 10 and 1000 kHz. The relative permeability μ is close to unity for non-magnetic fill material.

6.2 The Wenner array is useful for measuring conductivity below a few kilohertz but is unsuitable for determining permittivity at any frequency. The perpendicular array eliminates uncertainties in electrode contact but needs development to reduce further the inductive coupling between leads.

6.3 The sample chamber method is convenient to use but may underestimate the permittivity because the soil has been disturbed.

6.4 The high frequency in situ methods are limited by uncertain contact between the electrodes and soil. Performance is improved when the area of contact is maximized and insulation is used to prevent direct conduction.

7.0 RECOMMENDATIONS

The following recommendations should be considered for eventual implementation, in the medium distant future, following development of computational tools to analyze grounding systems under transient conditions:

7.1 The perpendicular array method described in Section 2.1 should be further developed to eliminate coupling between test leads.

7.2 The soil chamber method should be further developed using a guard screen to improve its accuracy.

7.3 The surface dipole and diamond methods should be tested using wider and longer screen-type electrodes.

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APPENDIX A

EVALUATION OF GROUNDING SYSTEMS AND WIRING PRACTICES WITH RESPECT TO ELECTROMAGNETIC INTERFERENCE

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1.0 INTRODUCTION

This proposal for a study by the Electrical Research Department would provide tools and procedures for use by the Electrical Design Department to reduce certain kinds of electromagnetic interference (EMI) at generating stations. Lightning strikes at Bruce GSB in August and October 1989 are believed responsible for the temporary unavailability of critical standby generators, unwarranted station service transfers, false annunciations and flashovers on dc supply wiring leading to fuse blowing. At that time, our immediate response was to recommend some additional bonding for the standby generator building. Subsequent field tests showed that these ad hoc changes provided an EMI reduction to about 30% of the original voltages and currents, assuming a strike to this building. Now we propose a more general study which will allow designers to calculate the benefits of various changes to grounding systems and low voltage wiring.

The study would focus on two areas. The first topic would cover the analysis of grounding grid transient voltage rise during lightning strikes. Particular attention would be paid to those parts of the grid intended to intercept lightning, as on the vacuum building, and to the interconnections with outlying buildings, for example between the powerhouse and standby generators. The second topic would cover the shielding and grounding practices for long low voltage cables, especially those running outside the powerhouse. These cables are thought capable of bringing external disturbances into the vulnerable control room area of the station.

We believe the Electrical Research Department is well positioned to undertake this study. For many years Stuart Harvey has investigated the high frequency propagation parameters for many types of low voltage wiring. This knowledge will allow the modelling of capacitive coupling and resonance in long cables, which we believe reduces the effectiveness of single-point grounding. Peter Dick is developing algorithms to calculate the transient voltages appearing on grounding systems with greater efficiently and accuracy. The CDEGS grounding analysis software recently purchased by the Transmission Stations Design Department would also be available as an alternative. The focus would be on providing simplified formulas, tables, graphs and guidelines which would move us in the direction of quantifying and comparing several kinds of mitigation. We note that the existing practices include few calculations, and are probably conservative in some areas and deficient in others.

2.0 ONTARIO HYDRO BACKGROUND

Considerable attention has been paid to the design of powerhouse grounding grids to ensure that 60 Hz ground potential rises during system fault conditions remain within levels safe for personnel and equipment. The procedures are well documented in manuals such as "Design Guide on Grounding Practices for Generating Stations" issued by the Electrical Design Department. With respect to voltage differences to the outside world, this generally implies that the station ground resistance is kept below a defined value by means of a sufficiently large ground grid and by interconnections with skywires.

Inside the powerhouse, structural steel and all enclosures of electrical equipment are interconnected by copper conductors to provide reliable and low impedance bonding.

At higher frequencies such as those associated with lightning or switching transients, additional factors such as the reactive self and mutual impedances of the conductors provide significant departures from the low-frequency behaviour. Unfortunately, grounding system analysis at high frequencies is more difficult than at 60 Hz, so existing design guides have tended to make only qualitative recommendations. For example, the lightning protection of tall structures may call for the use of an unspecified number of parallel, well distributed, conductors running as directly as possible to a crowfoot grounding grid. Also the benefits of locating the grounding grid close to low voltage cable ducts may not have been exploited.

Computer-related control and supervisory systems in generating stations are usually installed according to a single-point grounding scheme. Thus all signal circuits are commoned to the control room end transducer or dc supply. Also cable shields are usually grounded only at the nearby distribution frames, on which all remote cables are terminated. Quite similar precautions are taken in a digital telephone exchange, in which the distribution frames cover an entire building and cables run throughout a city. Here power ground, equipment chassis ground, battery (including subscriber loop) ground and digital signal grounds may be interconnected at only one point in the building basement. In both utilities, the objective is to reduce the conductive coupling of disturbances from the power system into the control wiring.

Such arrangements generally provide good mitigation against interference in short cable systems (say under 100 m). In long cables such as in telephone systems (say more than 1000 m), voltage rises due to lightning tend to be localized to only part of the cable, the long distances promote losses and the operation of protective gaps at terminal equipment is acceptable. Unfortunately, the intermediate length cables found in our nuclear stations appear to be particularly vulnerable to both localized ground rise and medium frequency resonances (10 - 100 kHz) in the shield to ground mode.

The study will provide tools for investigating these types of problems as well as looking at innovative methods of mitigation. For example, the local ground potential rise might be reduced using low inductance conductors based on expanded steel meshes. Cable shielding might be improved using lossy shield terminations. Greater dielectric withstand might be useful for cables leaving the powerhouse.

3.0 PROJECT OBJECTIVES

3.1 Control of Transient Ground Potential Rise

Develop a clear understanding of the transient potentials appearing on power/lightning grounding systems as installed at nuclear generating stations when structures or buildings are struck by lightning. Determine the effect of changes in ground grid geometry, conductor size and the sensitivity of secondary parameters such as soil resistivity and permittivity. Generalize the results towards simple formulas for use by system designers. Identify system configurations or protection schemes which might reduce the transient stresses experienced by control or supervisory wiring.

3.2 Improved Shielding of Control and Supervisory Wiring

Determine the mechanisms by which lightning-induced transient potentials can couple to shielded control and supervisory wiring as used in nuclear generating stations. Develop an understanding of the effects of broadband transient voltages and currents on cables with single-point grounded shields. Propose methods by which control and supervisory cables can be shielded against lightning-induced interference without compromising "clean" computer grounding systems.

4.0 PROPOSED RESEARCH PROGRAM

The proposed research program would have three stages to divide the work administratively. The first stage would begin the development of research tools. The end of this stage late in 1990 would provide an opportunity for feedback and allow for changes in direction. The second stage would continue tool development and cover the analysis of existing grounding and wiring practices. The third stage is presently tentative and would cover design innovations. It could begin late in 1991 or early 1992 and would require funding beyond the $100 000 limit presently assumed. Each stage is divided into area A - Grounding Systems - covered by the System Studies Section and area B - Station Wiring - covered by the Science Section. Stage 2-A is further divided into Tasks a to d, which together with the other stages have approximately equal funding requirements of $15 000 each. Reports would be issued at the end of each stage.

In the near term, a heuristic review of the particular grounding practices in place at Bruce GSA could be accommodated but this has been kept separate from the larger project. In the longer term, changes made in grounding or wiring practices as a result of the project could be tested as a separately-funded item.

Stage 1-A: Grounding Systems Soil Parameters

Conduct field tests to determine representative values for soil resistivity and permittivity, as well as their frequency dependence, from low frequency to 1 MHz. This would be based on in situ tests using a Wenner array, a network analyzer and a suitable set of connecting cables to remove the effect of inductive coupling from the results. The tests would be conducted in an unused part of the Bruce NPD site.

Stage 1-B: Station Wiring Modelling

Conduct tests to determine propagation parameters of representative cables from low frequency to 1 MHz. These would be conducted in the Research Lab, where other systems vulnerable to interference are absent. Analyze the results and develop models to generalize the results. Verify model predictions and conduct further tests to resolve differences. Implement research tools to simulate the shielding performance of station wiring.

Stage 2-A: Grounding Systems Analysis

This stage would cover the development of research software tools, tests to validate these tools, a review of existing grounding practices and the development of practical guidelines, formulas and software for use by station designers:

a) Compare a number of computer programs suitable for simulating a grounding grid under transient conditions including MALTZ (part of Safe Electric Systems, Montreal, CDEGS grounding analysis package), the ElectroMagnetic Transients Program [see attached IEEE paper] and in-house software being developed with advanced capabilities for including full inductive coupling between all elements of multiple grid elements.

b) Validate the software by measuring the transient potentials and currents appearing on a simplified set of grounding conductors installed at a site near the Research Lab, where other systems vulnerable to interference are absent. The conductors would be temporarily placed on the soil surface and their distributed connection to the ground would be approximated by a number of vertical probes pushed about 25 cm into the soil.

c) Establish the general performance of existing designs. Develop tools for determining the integrity of existing grids. Using grid geometries from Bruce GSB, simulate the potential profiles of the grounding system and soil located in the vicinity of a lightning strike. Calculate transient currents in grid conductors and the potentials induced along prospective cable paths. Compare the results with those measured at Bruce GSB in 1989.

d) Provide software for analyzing grounding performance. Generalize the above results in the form of guidelines, empirical or simplified formulas and tables for use by grounding system designers. Quantify the relative performance of different geometries and parameter values so that their benefit to cost ratio can be compared.

Stage 2-B: Station Wiring Existing Practices

Establish the shielding effectiveness of existing configurations, including existing practices such as the use of "clean grounds", using the research tools of Stage 1. Analyze the sensitivity of the results to changes in cable length, shield construction, shield grounding practices and grounding system design, identifying geometries which are particularly vulnerable. Using wiring configurations for Bruce GSB standby generator SG5, simulate the tests conducted in 1989 and compare to measured data.

Stage 3-A: Grounding Systems Innovations

Select a number of simplified grid geometries to be simulated including: a uniform mesh extending practically to infinity in all directions, the edge of a semi-infinite plane, the corner of a semi-infinite quadrant, as well as the end of a long and narrow (peninsular) grid. Investigate changes in other parameters such as ground resistivity, permittivity (capacitance), chemical treatment, conductor size and mesh size. Study innovative grounding systems including expanded strip aluminum or steel meshes, diverter towers and new crowfoot (radial) geometries for tall buildings likely to be struck by lightning.

Stage 3-B: Station Wiring Innovations

Study the use of innovative techniques such as grounding "islands", coaxial termination of shields, shield termination devices which could damp transient modes and changes to the grounding system which would improve the shielding effectiveness of station wiring. Provide guidelines for quantifying the relative performance of these innovative wiring systems.

5.0 PROJECT SCHEDULE, FUNDING

The first stage of the project would be completed in 1990 followed by a review. The second and third stages could start late in 1990 and 1991 respectively. We estimate the following costs for each stage:

Stage 1-A: Grounding Systems Soil Parameters	15 000
Stage 1-B: Station Wiring Modelling	15 000
Stage 2-A: Grounding Systems Analysis	60 000
Stage 2-B: Station Wiring Existing Practices	10 000
Stage 3-A: Grounding Systems Innovations	15 000
Stage 3-B: Station Wiring Innovations	20 000

6.0 PROJECT DELIVERABLES

Stage 1-A: Grounding Systems Soil Parameters

Development of a test method for finding soil parameters at high frequencies. Results for the Bruce GSB site.

Stage 1-B: Station Wiring Modelling

Development of a test method for finding cable parameters at high frequencies and research tools for simulating station wiring systems.

Stage 2-A: Grounding Systems Analysis

a) Review of existing software and tools developed at the Research Lab with advanced capabilities.

b) Experimental results using "mock" grids for future validation of grounding analysis software.

c) Identification of areas in existing grounding practices needing improvement. Test methods for finding weak or open conductors in existing grids. Models to generalize the 1989 tests.

d) Simplified formulas, tables, and empirical guidelines to allow designers to quantify the performance of existing or new grounding systems.

Stage 2-B: Station Wiring Existing Practices

Identification of areas in existing wiring practices needing improvements. Models to generalize the 1989 tests.

Stage 3-A: Grounding Systems Innovations

A description of innovative grounding practices using new geometries and materials to be considered in future designs.

Stage 3-B: Station Wiring Innovations

Comparisons of innovative wiring practices and quantitative guidelines for analyzing their shielding effectiveness.

7.0 CONCLUSIONS

Interference to nuclear generating station control equipment from disturbances such as lightning, switching and power system faults may be coupled through long signal cables. Existing design practices such as single-point shield and signal common grounding, and extensive ground meshes in buildings have reduced but not eliminated the problem. Typically, long cables are subject to resonant modes in a noisy part of the disturbance spectrum, while the power frequency ground system could be optimized to be more beneficial at higher frequencies. This proposal describes a comprehensive study of this coordination problem. The measurements will be generalized by authoritative analytical modelling. The results are expected to provide designers with quantitative tools as well as identifying areas in the grounding and cable wiring systems needing improvement.

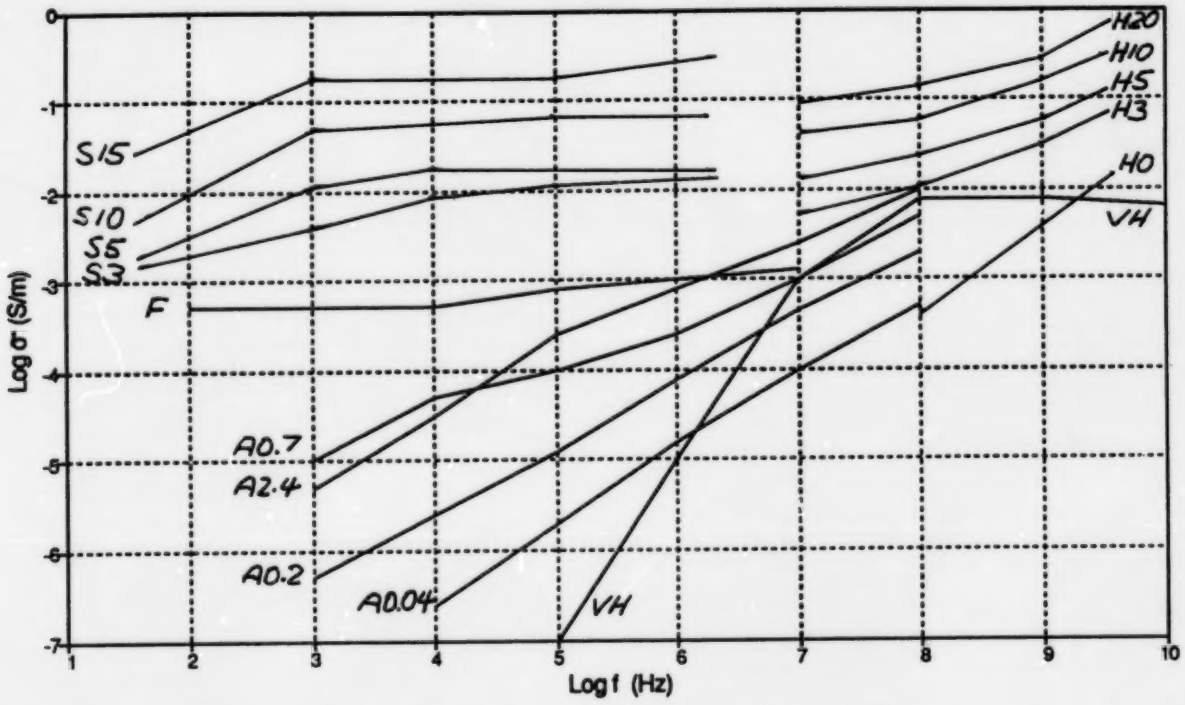

Figure 1 Frequency-dependent conductivities reported in the literature.

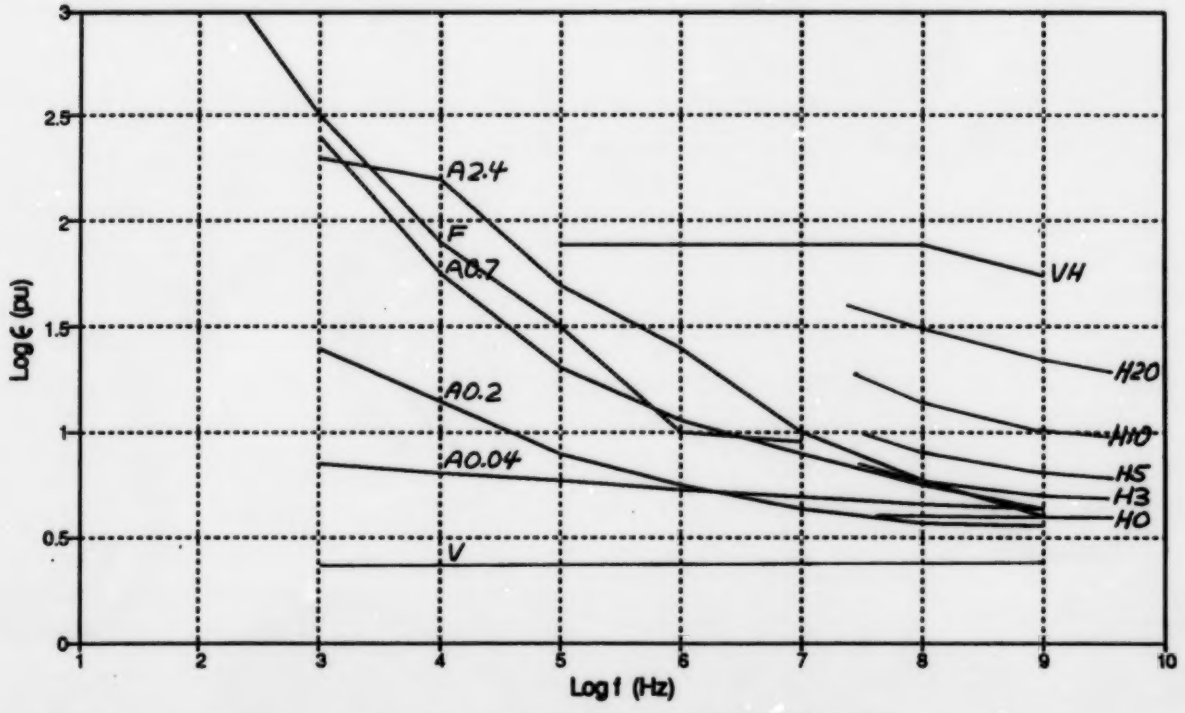

Figure 2 Frequency-dependent permittivities reported in the literature.

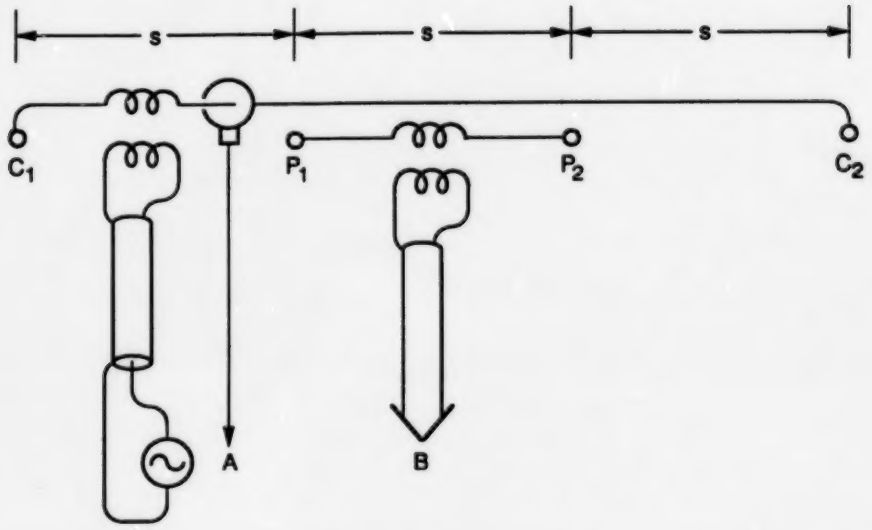

Figure 3 Configuration of classic Wenner array.

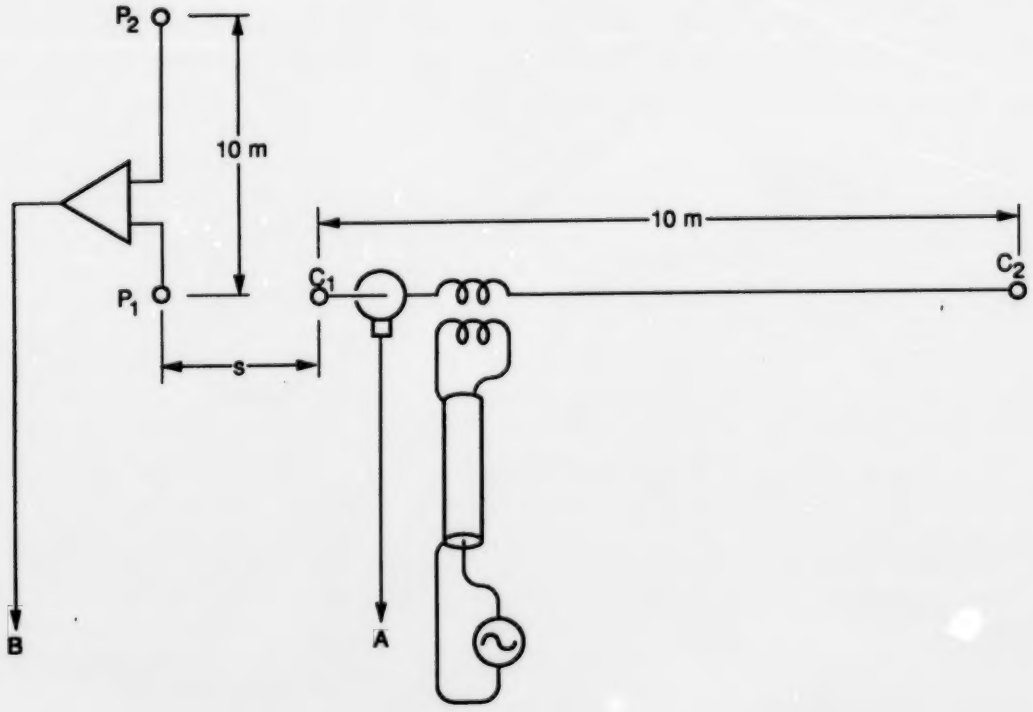

Figure 4 Configuration of modified Wenner array with perpendicular current and potential leads.

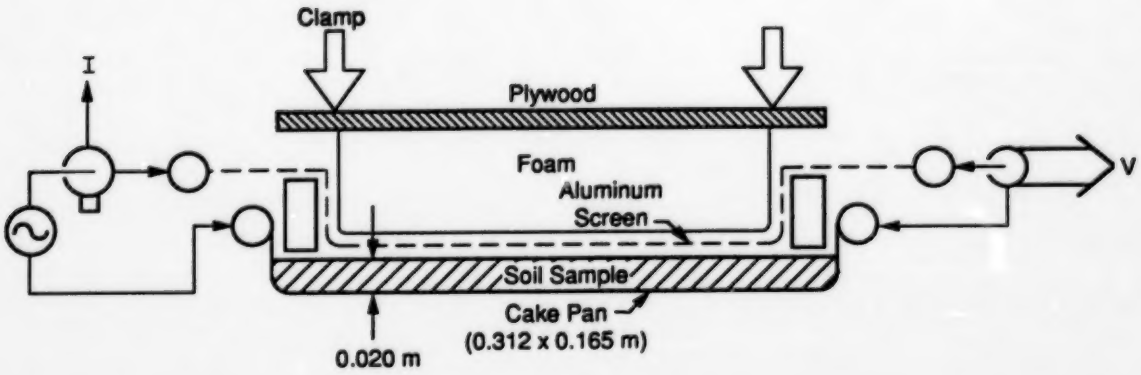

Figure 5 Configuration of lumped admittance sample chamber.

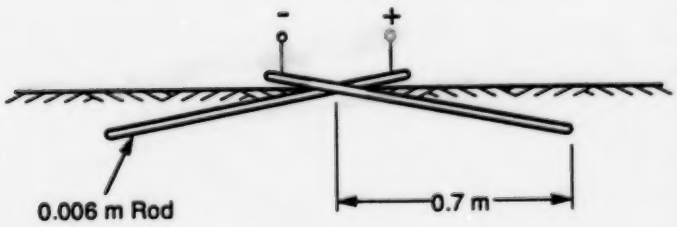

Figure 6 Configuration of buried rod dipole.

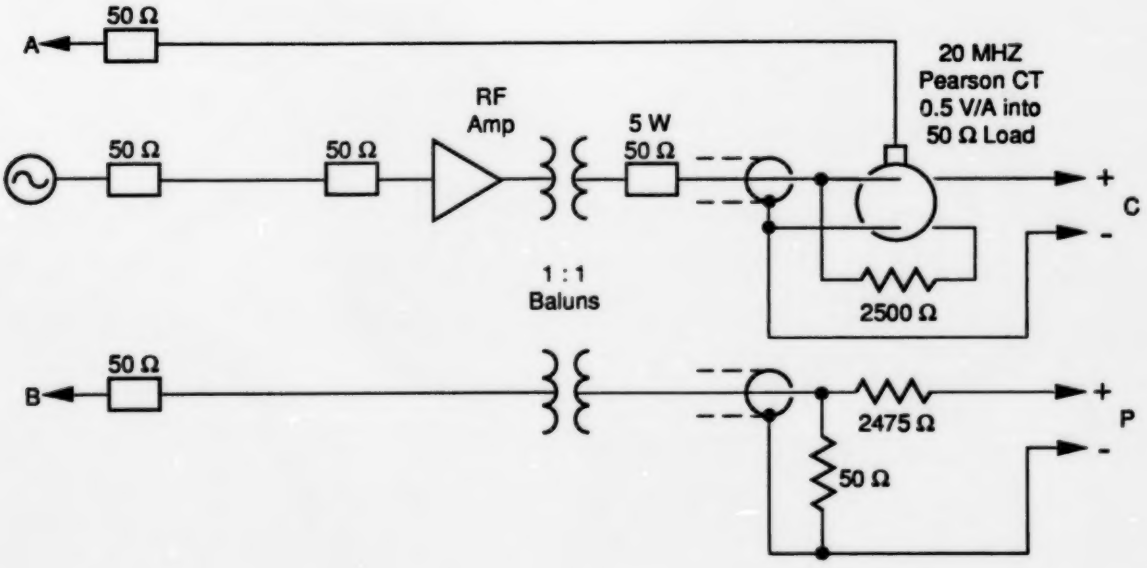

Figure 7 Instrumentation for measuring balanced admittance.

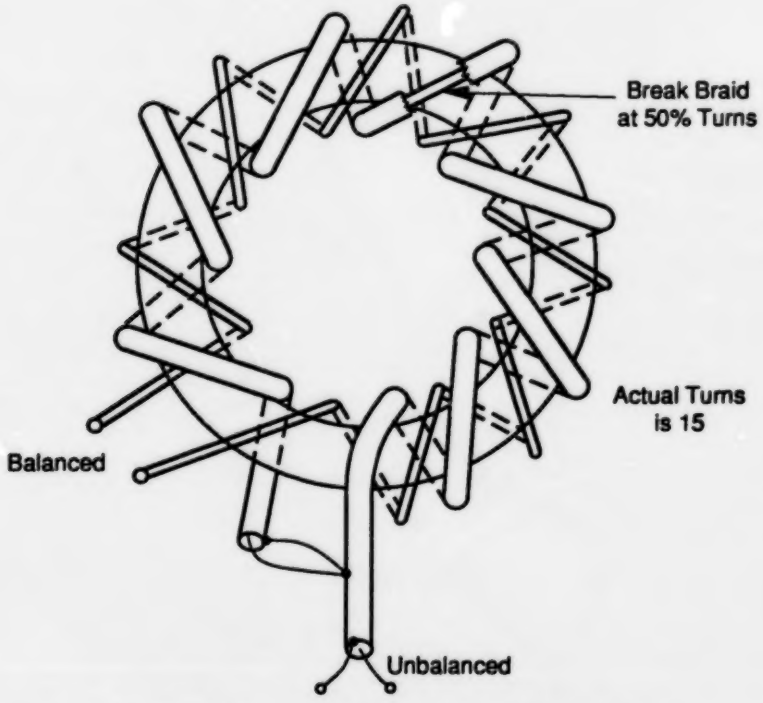

Figure 8 Configuration of balun with balanced capacitive coupling.

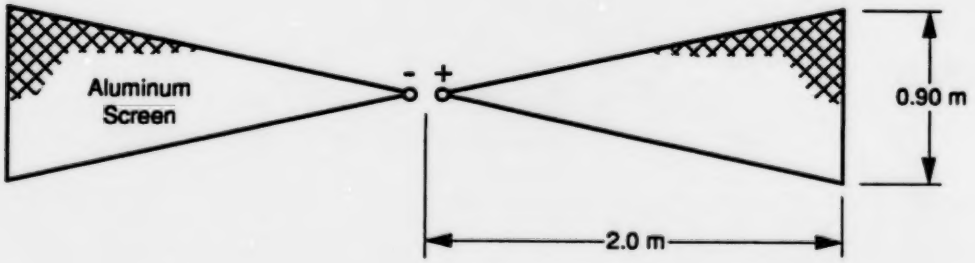

Figure 9 Configuration of surface bowtie dipole.

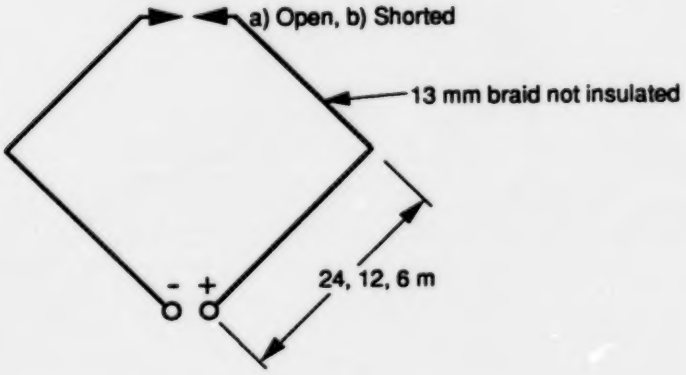

Figure 10 Configuration of surface braid diamond.

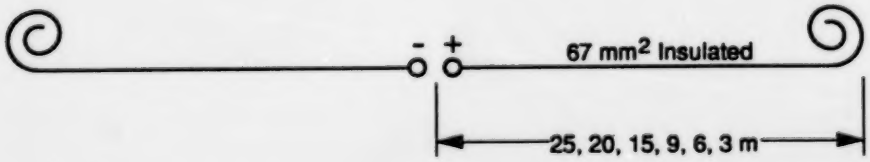

Figure 11 Configuration of surface cable dipole.

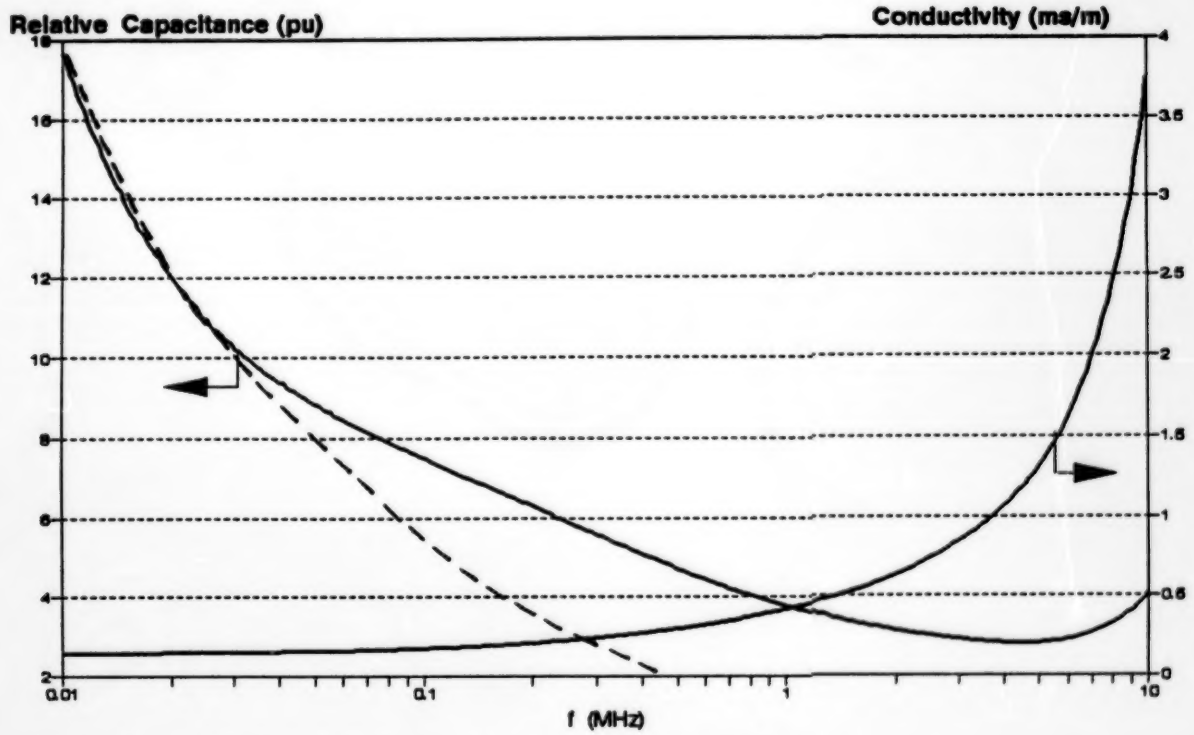

Figure 12 Sample chamber results for Bruce NGS fill material.

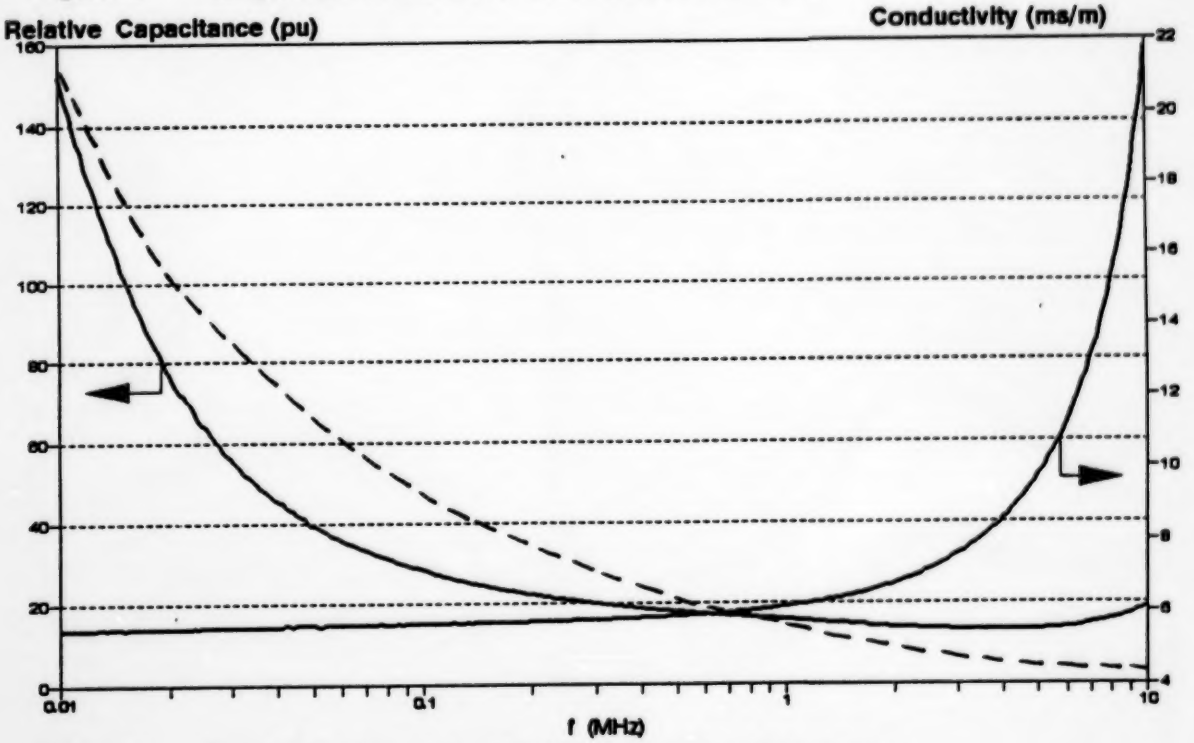

Figure 13 Sample chamber results with 10 % increased water content.

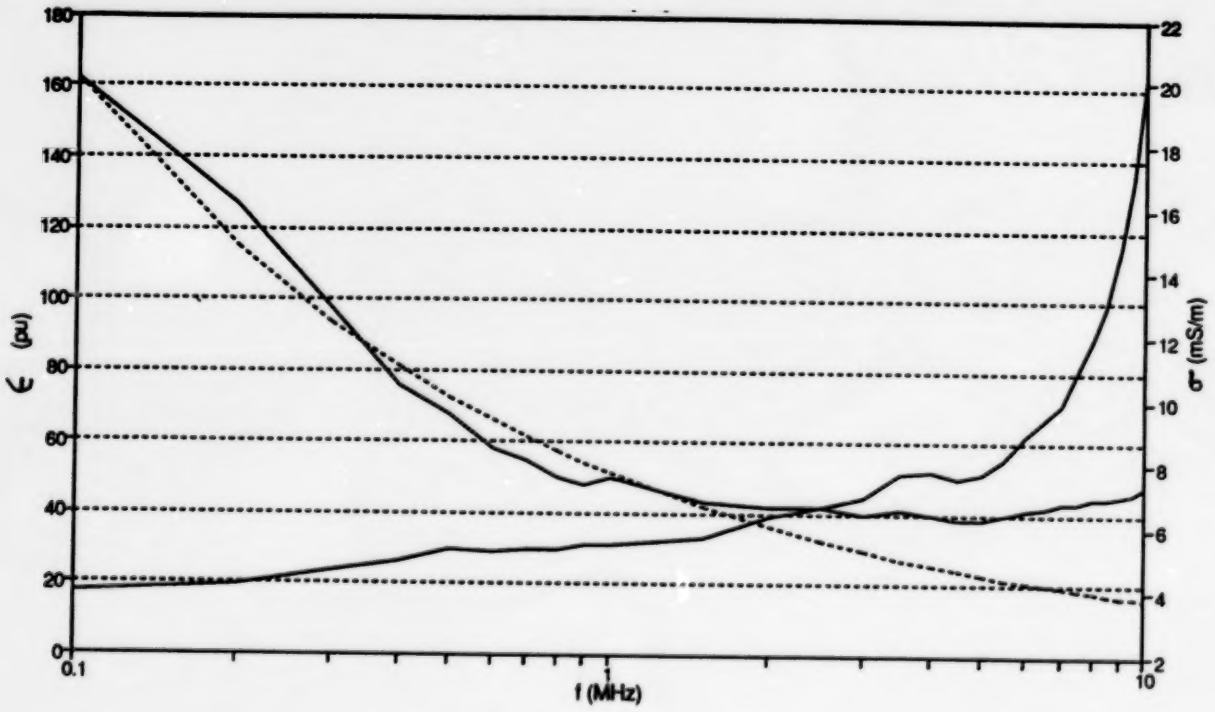

Figure 14 Test results for buried rod dipole.

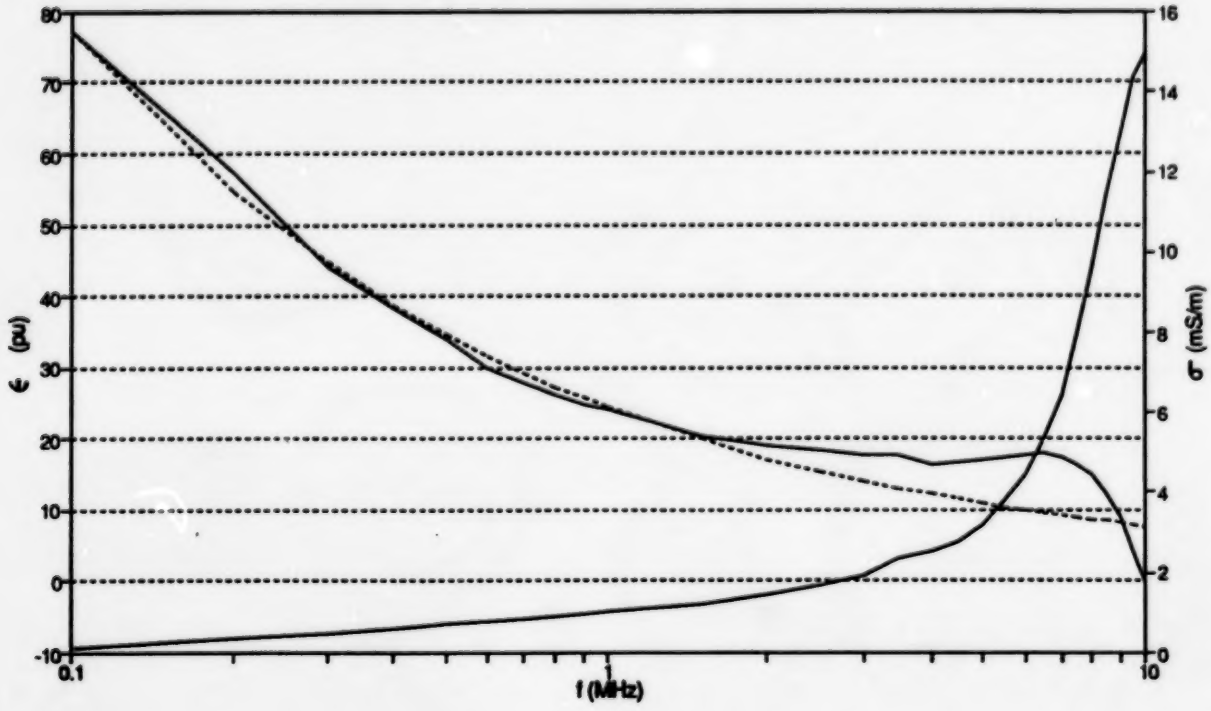

Figure 15 Test results for surface bowtie dipole.

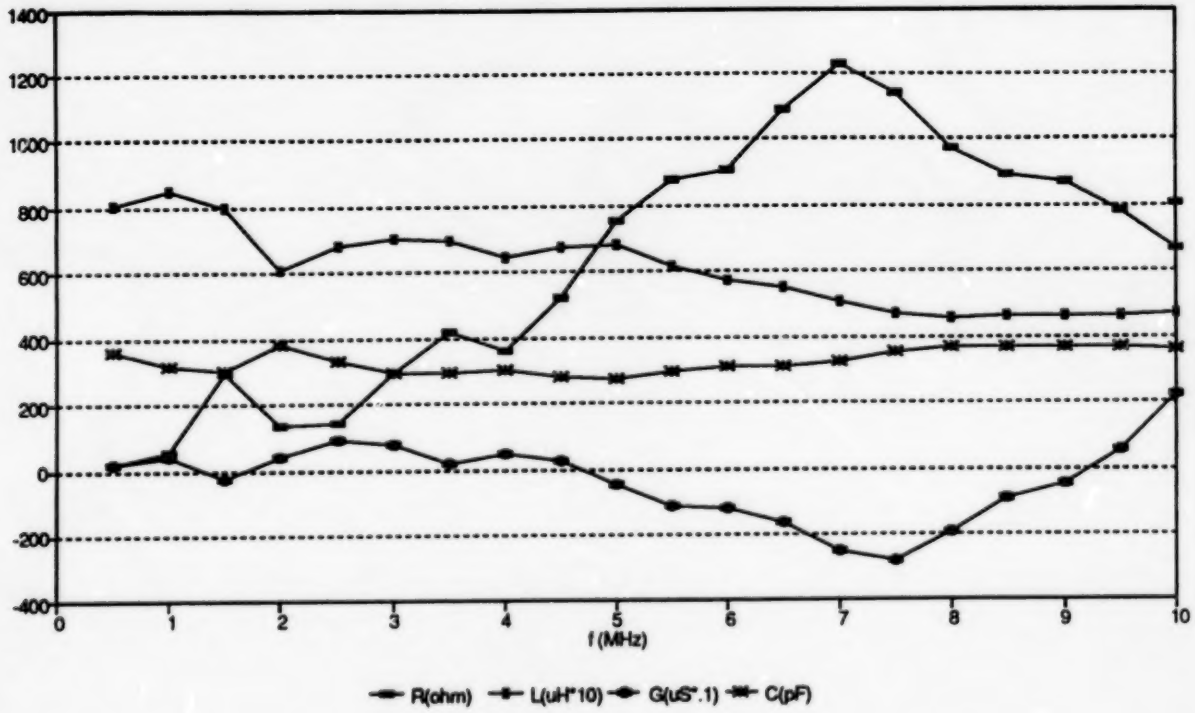

Figure 16 Tested per unit length parameters for surface braid diamond.

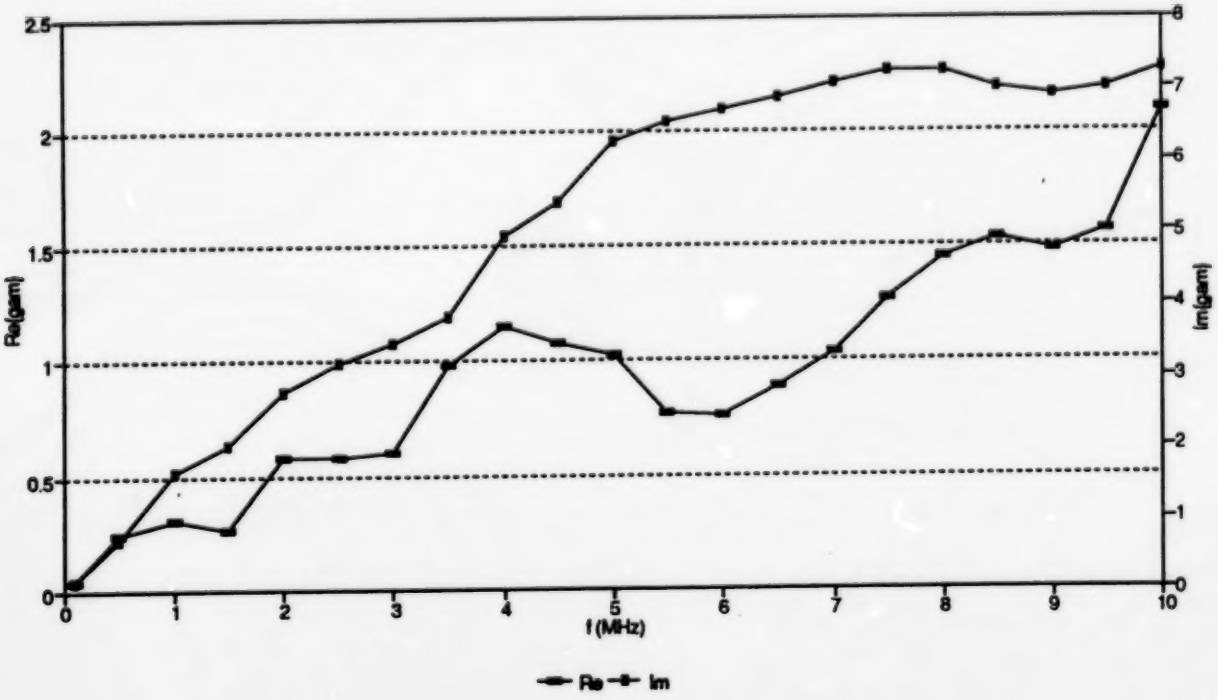

Figure 17. Propagation characteristics for surface cable dipole.

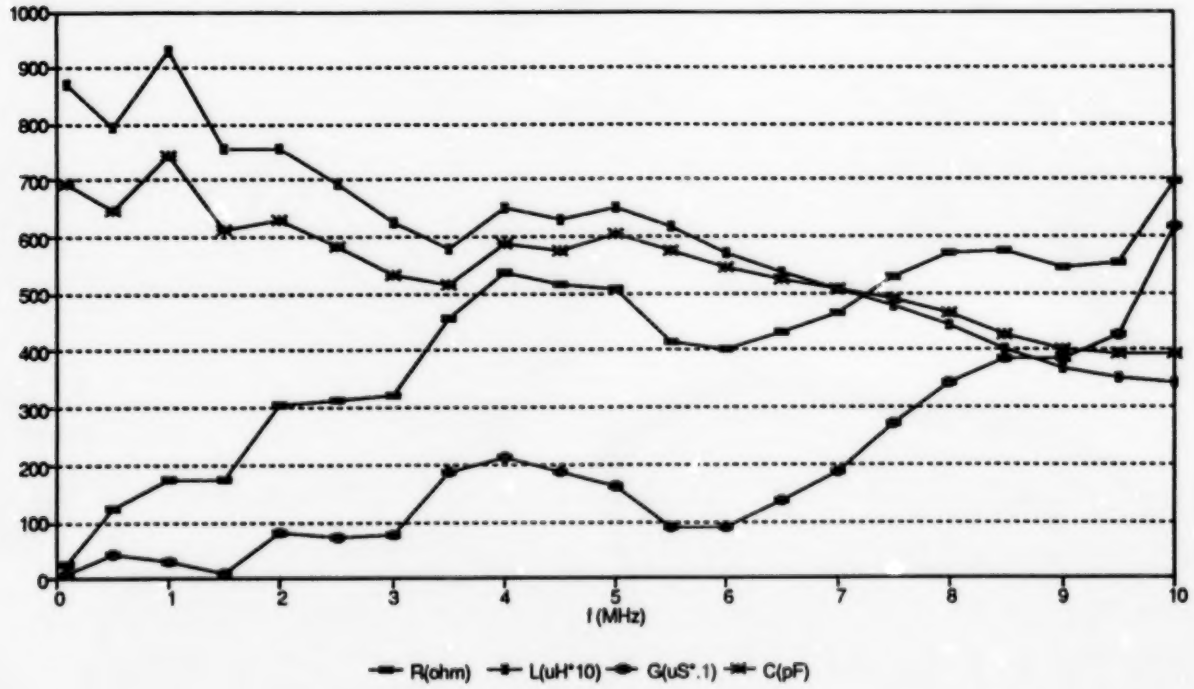

Figure 18 Per unit length parameters for surface cable dipole.